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SUMMARY

A turbine noise prediction method for interim use in the NASA Aircraft Noise Prediction Program is selected. The method predicts the level, directivity, and one-third octave band spectra of far field turbine noise as a function of engine parameters. The selection results from a review of turbine noise data and prediction methods available in the open literature. It is concluded that the state-of-the-art turbine noise prediction capability is primitive and that the selected method represents only a temporary interim approach. Recommendations are made on research requirements.

INTRODUCTION

With reduction of fan noise (through noise-reduction design features and fan duct suppression treatment) and of jet noise (as characterized by high bypass ratio turbofan engines), the turbine can become a contributor to the overall propulsion system noise (see references 1 and 2) and hence requires consideration for proper determination of aircraft flyover noise levels.

The purpose of this report is to recommend a method for predicting turbine noise as a component of total aircraft noise for the NASA Aircraft Noise Prediction Program (ANOPP). This Program is being developed at Langley Research Center in conjunction with other NASA Centers and with help from industry representatives. In the Program, the various

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contributors and modifiers of aircraft noise are summed at various locations in order to predict a noise footprint for single- or multiple-event aircraft flights. It is required that this prediction method be based on the present state-of-the-art, and that the method predicts the level, directivity, and spectra of turbine noise in terms of convenient engine parameters.

Limited experimental data on turbine noise are available from both turbine-rig and full-scale-engine tests. The earliest published evidence of the existence and potential importance of turbine noise was presented by Smith and Bushell (Reference 1). The most convincing evidence reported by Smith and Bushell was the existence of a clearly defined tone at the turbine blade passage frequency. The data in Reference 1 were obtained from both a turbine rig and full-scale engines. Turbine noise data for the NASA Quiet Engine C are reported in Reference 2.

The first published turbine noise correlation was presented in Reference 1. The correlation approach was based on the assumption that the mechanisms of noise generation for a turbine were comparable to mechanisms of noise generation for a fan. Two types of noise, discrete tones and broadband (referred to as "vortex" in Reference 1) noise, were considered separately for correlation. The tone noise was reported to result from the cyclic interception of the guide vane wakes by the rotor blades and the interaction of the rotor wakes with the following vane row. The broadband noise was described as resulting from random lift fluctuations on both the rotors and the stators. Reasonable success was achieved in correlating the broadband noise. However, correlation attempts for the turbine tones did not reduce the scatter of the plotted data sufficiently to reveal any trends.

Other turbine noise correlations that currently exist in the literature, are those presented by Dunn and Peart in Reference 3, by Matthews, Nagel, and Kester in Reference 4, and by Kazin and Matta in Reference 5.

The method which is recommended herein for ANOPP use is that presented by Dunn and Peart in Reference 3. This method is basically as derived by Smith and Bushell, but the predicted levels have been adjusted by Dunn and Peart to agree with available turbine noise data from turbofan engines. An alternate procedure for predicting turbine noise is also proposed herein. This is the correlation of Kazin and Matta, Reference 5, based on data from several General Electric engines.

TURBINE NOISE EXPERIMENTAL MEASUREMENTS

Turbine noise measurements from a special turbine test rig and from full-scale engine static tests have been reported in the literature by various investigators. The tests reported in Reference 1 were conducted with single- and two-stage cold model turbines. The data from these tests show that turbine noise consists of broadband noise and tones at harmonics of the blade passage frequency. The tones peaked at angles ranging from 120 degrees to 140 degrees from the inlet. The broadband noise peaked at 100 degrees to 120 degrees from the inlet. Comparison of the rig data for one- and two-stage turbines with data from engines having three- or four-stage turbines showed a systematic increase of the broadband noise with increasing number of stages. Similar comparisons for the tone were inconclusive

The full-scale engine tests reported in References 2 and 6 for NASA Quiet Engines C and A, respectively, were performed for a number of engine configurations incorporating acoustic treatment for different noise sources. One objective of the program was to develop and evaluate acoustic treatment linings for suppression of turbine generated noise. Such tests on full-scale engine configurations in which the fan noise is highly suppressed provide information on turbine noise. The accuracy and detail of description of the deduced turbine noise depends on the intensity of the turbine noise relative to other sources and hence, on how well obscuring noise sources are identified and either suppressed or accounted for. Figure 1 shows far-field one-third octave band spectra at 120 degrees from the inlet for Quiet Engine C with and without turbine noise acoustic treatment. In both cases the fan noise was highly suppressed. Without turbine noise acoustic treatment, a spike in the spectrum occurs in the 6300 hz. band, which contains the blade passage frequency of the last two stages of the turbine. The fact that acoustic treatment, located in the engine core downstream of the turbine, significantly reduced this spike verified that this spike originated in the core engine and that other sources did not obscure the turbine tone.

TURBINE NOISE CORRELATIONS

In arriving at an empirical correlation of turbine noise data obtained from turbine rig and full-scale engine tests, Smith and Bushell first considered the possible governing parameters assuming correspondence between the noise generation mechanisms of the fan/compressor and those of the turbine. Because of difficulties in determining or adequately describing some of the possible governing parameters (e.g. turbine-blade life curve slope, turbulence intensity) Smith and Bushell limited the number of parameters utilized in the correlation attempt. Turbine broadband noise and discrete tones were considered separately. The prime correlation parameter for both broadband noise and discrete tones was chosen to be the blade relative velocity, V_{rel}. The function chosen to describe the broadband noise also included the effects of the turbine size in terms of the mass flow, m, and the local speed of sound, a. The equation for the peak sound pressure level of the broadband noise suggested by data obtained for single- and two-stage model turbines and for full-scale engine 3- and 4-stage turbines is given as:

$$SPL_{\substack{PEAK,\\BROADBAND}} = K + 10 \log m + 30 \log \frac{1116}{a} + 30 \log V_{rel}$$

When correlated against final rotor V_{rel}, sound levels from the two-stage model turbine were about 12 or 13 dB higher than the single-stage model. This difference was attributed to the effects of turbulence level of the air entering the second stage of the two-stage model turbine (the approaching air was nearly turbulence-free for both model turbines). The levels for the full-scale engine turbines are slightly higher than for the two-stage turbine model (e.g., the turbine noise for the full-scale engine with three turbine stages is about 2.5 dB higher than for the two-stage model turbine and the four stage engine data fall above the three stage). Smith and Bushell interpreted this result to indicate that there is a 10 $\log_{10}N$ relationship with number of stages.

For discrete tones, the correlation also included the effect of stator-rotor spacing to chord ratio, S/C. Empirical correlation attempts for the discrete tone levels were inconclusive because of the large data scatter. The correlation attempt is shown as a plot of

$$\left(SPL_{\substack{peak\\tone}} - 10 \log m + 20 \log \frac{S}{C} - 30 \log \frac{1116}{a}\right) \text{ versus } \log V_{rel}$$

for both full-scale and model results, where the tone is the final stage fundamental and V_{rel} is the final-stage blade relative velocity. The full-scale results roughly suggest a 10 log $V_{rel}^{0.6}$ relationship whereas the model results are inconclusive because of the larger scatter.

Dunn and Peart (Reference 3) present calculational procedures for predicting ground noise contours during the single-event takeoffs fly-overs, and/or landing operations of aircraft. The calculational procedures include formulations for the component noise sources. The formulation for the turbine is essentially as derived by Smith and Bushell. However, Dunn and Peart use 10 log S/C to account for the spacing effect on tones, whereas Smith and Bushell used 20 log S/C. The sound pressure level given by the predictive method was adjusted by Dunn and Peart to give best overall agreement with limited turbine noise data inferred from turbofan engine data as shown by the solid lines in figure 2 (taken from Reference 3). A special case in the prediction procedure is the JT8D engine which mixes the core and fan flow internally. Dunn and Peart recommend that the level of the predicted tone be reduced by 10 dB for this engine (dashed line). Others have observed changes in turbine spectral shape with changes in core exhaust geometries. The deviation of individual data points from the established prediction line ranges up to ± 5 dB for the fundamental tone and ± 9 dB for broadband noise. The data scatter is large and the prediction capability is unsatisfactory. Spectra and directivity curves are also given in Reference 3 for discrete tone and broadband noise separately. Both turbine-noise components are highly directional, peaking at about 110 degrees from the inlet. Details of this procedure are given in the Appendix of this report.

In Reference 4, Mathews, Nagel and Kester state that they were able to collapse turbine noise data from JT9D, JT8D, and JT3D engines. The data, when plotted against turbine last stage tip speed, were collapsed by including the effects of mass flow, number of stages, blade/vane spacing, turbine inlet temperature, and turbine work. Although an equation for the correlation is not presented, it is stated that the dominant parameters in the procedure are turbine work and turbine speed. The work term was needed to collapse the data from an engine with a highly loaded turbine and those from engines with lightly loaded turbines. Since the details of the form of this correlation were not presented, it could not be considered for the NASA Aircraft Noise Prediction Program.

In Reference 5, Kazin and Matta present a correlation of turbine noise from several General Electric engines. This correlation was developed under contract to FAA, as part of the GE/FAA Core Engine Noise Control Program, which was started in June 1973 and includes experimental investigation of turbine noise and development of an analytical turbine noise model. Two forms of correlations are presented. The first, referred to as a "preliminary prediction method" predicts turbine sound levels in terms of overall turbine pressure ratio, the blade tip speed of the last stage, and the core nozzle exit area. The equation for the overall sound pressure level is:

$$\text{PEAK OASPL} = 40 \log_{10} (\Delta T/T)_{\text{Turbine}} - 20 \log_{10} U_T + 10 \log_{10} A + 164$$

where PEAK OASPL = overall sound pressure level at 120 degrees and 60.96 m. (200 ft) sideline in dB re $20\mu N/M^2$ and includes extra ground attenuation and standard day air attenuation; and where

$$\left(\frac{\Delta T}{T}\right)_{Turbine} = 1 - \left(\frac{1}{P_r}\right)^{\frac{\gamma - 1}{\gamma}}$$

P_r = turbine total-to-static pressure ratio (PTo/PS2)

U_T = blade tip speed of last stage, M/sec

A = core nozzle area, M^2

γ = ratio of specific heats, ~ 1.4

Spectra and directivities are not provided for the preliminary prediction method.

The second correlation, referred to as the "comprehensive prediction method", predicts the noise generated by each stage individually. Two equations for level, one for broadband plus tone and one for tone, are given. These are:

$$\text{PEAK OASPL} = 8.75 \log_{10}\left(\frac{\Delta T}{T}\right)_{stage} + 20 \log_{10}\left(\frac{V_{rel}}{a}\right)$$

$$+ 10 \log_{10} A - 5 \log_{10}\left(\frac{2S}{L}\right) + 113.2$$

$$\text{PEAK SPL} = 21 \log_{10}\left(\frac{\Delta T}{T}\right)_{stage} - 20 \log_{10} (U_T) - 10 \log_{10}\left(\frac{2S}{L}\right)$$

$$+ 161.5 + 10 \log_{10} A$$

where PEAK OASPL = combined broadband and discrete frequency OASPL at 120 degrees and 60.96 M (200 ft.) sideline in dB re 20 $\mu N/M^2$ and includes extra ground and standard day air attenuations.

PEAK SPL = tone SPL at 120 degrees and 60.96 M. (200 ft.) sideline, without air attenuation and EGA, in dB re 20 $\mu N/M^2$. Here,

$$\left(\frac{\Delta T}{T}\right)_{stage} = 1 - \left(\frac{1}{Pr_{stg}}\right)^{\frac{\gamma - 1}{\gamma}}$$

PR_{stg} = stage total-to-static pressure ratio

V_{rel} = tip blade relative velocity at inlet to the rotor, M/sec

U_T = blade tip speed, M/sec

a = acoustic velocity at inlet to the rotor, M/sec.

A = turbine stage exit area, M^2

S/L = axial spacing/upstream blade chord

γ = ratio of specific heats, $\sim$1.4

Directivities are given for both the OASPL and the tone SPL at takeoff and approach power settings. However, these power settings are not defined in terms of turbine parameters, nor are procedures presented for determining the directivities at other power settings. At each far-field angle, the tone SPL is antilogarithmically subtracted from the composite OASPL to yield a broadband noise OASPL. Spectra for the broadband noise are presented for takeoff and approach conditions

COMPARISON WITH DATA

Some turbine noise data available at NASA-Lewis Research Center from several turbofan engines were compared with predicted turbine noise using the methods of References 3 and 5. Figure 3 is a plot of the difference between predicted turbine noise, using the method of Reference 3, and measured turbine noise plotted against tip speed. Differences between predicted and measured levels range from -6 to +8 dB. Attempts to decrease the scatter by including a turbine work term failed.

Figure 4 is a plot of the difference between predicted levels, using the "preliminary prediction method" of Reference 5, and measured turbine levels. Differences range from -4 to +8 db, usually with a given engine being either over- or under-predicted. Detailed data were not available to make comparisons of the "comprehensive prediction procedure" of Reference 5 with data.

Some comparison of the methods of Reference 3 and 5 with data from the JT8D-109 refan engine are presented in Reference 4. The method of Reference 3, referred to as the "NASA Method" in Reference 4, under-predicts the refan data by about 5dB at low speeds, but goes through the data at high speeds. The methods of Reference 5 predicts levels about 2 dB lower than those of Reference 3.

RECOMMENDED INTERIM METHOD FOR ESTIMATING TURBINE NOISE

Based on the preceding comparisons, both of which are based on limited data, there does not appear to be any significant difference in the accuracy of either the method of Reference 3 or the "preliminary prediction procedure" of Reference 5. The "preliminary prediction procedure" of Reference 5 cannot itself be considered for ANOPP since it does not include estimates of directivity or spectra. However, the "comprehensive prediction procedure" of Reference 5, which does include estimates of spectra and directivity, presumably has the potential to be more accurate since it has separate predictions for broadband and tone noise. Because data were not available to verify this presumption, and because the method of Dunn and Peart, Reference 3, was indicated as the recommended procedure prior to the publication of Reference 5, the method of Dunn and Peart will still be considered to be the recommended procedure. However, the comprehensive prediction procedure should be considered as an equally accurate alternate procedure.

TURBINE NOISE RESEARCH REQUIREMENTS

A systematic experimental/analytical program specifically directed at investigation of turbine noise generation mechanisms is required. The experimental part of the program should consist of both engine and rig tests. Analytical work is needed to guide the experimental work and to understand the results.

Turbine noise has been observed and measured on a variety of existing engines. Typically, however, noise and operational data from only a few of these engines are available to a given researcher. The existing data need to be collected and correlation attempts need to be made. Additional engine tests should be made to increase the existing data base to investigate particular trends, and to take more detailed measurements to define the turbine noise generation mechanisms.

A turbine noise facility is needed in order to provide the following elements which are difficult to obtain on a full-scale engine and which are necessary for systematic investigation of turbine noise mechanisms:

(a) a low background noise environment;

(b) a high degree of flexibility in setting up and testing different turbines and turbine modifications;

(c) capability of testing over a wide range of operating conditions;

(d) capability of independent control of the important variables affecting turbine noise (e.g., turbulence level and structure in the upstream turbine flow); and

(e) convenience of instrumentation placement and maintenance which makes for more detailed instrumentation than possible or practical in engine tests.

The turbine noise experimental program should include measurements to define the noise generation and attenuation associated with each turbine blade and vane row. Measurements in the exhaust duct would help to isolate the effects of exhaust geometry and flow on the transmission of turbine noise to the far field. Special probes may have to be developed to make these measurements.

CONCLUDING REMARKS

The primary purpose of this report is to select an interim method for predicting turbine noise for use in the NASA Aircraft Noise prediction Program. Turbine noise data and correlations available in the open literature are reviewed and a recommendation made. However, due to the limited data available and the amount of scatter in these data, the recommended procedure should be viewed as a temporary method. As more data become available the method should be reevaluated and modified or replaced as warranted.

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APPENDIX

The turbine noise prediction method of Dunn and Peart (Reference 3) is presented herein. The sound pressure levels are for 45.7 meter radius from the source which can be corrected to 1-meter radius through application of spherical divergence and atmospheric absorption corrections as indicated herein. Note that the term $(1 - M_0 \cos \xi)^{-4}$ appearing in equations (1) and (4) represents the sound level amplification due to source motion.

TURBINE NOISE PREDICTION

The turbine noise prediction procedure considers two noise components: broadband and discrete tone. Both components have been related to the relative tip speed of the turbine's last stage, the primary mass flow, and local speed of sound at the turbine exit. The effects of stator/rotor spacing on the discrete tone levels is also considered.

It has been assumed that both components have spectra shapes that normalize with respect to the fundamental blade passage frequency of the last stage of the turbine. The predicted spectra are given in terms of 1/3 octave band levels (dB re 20 μ N/M^2) at the free-field, index (R=1M) conditions.

Broadband component - The relation for the peak 1/3 octave band level at a radius of 45.7 M (150 ft.) from the source is

$$SPL_{peak} \simeq 10 \log_{10}\left[\left(\frac{V_{TR}\ C_R}{V_R\ C_L}\right)^3 \left(\frac{\dot{m}}{\dot{m}_R}\right)(1 - M_0 \cos\xi)^{-4}\right] + F_1(\theta) - 10 \qquad (1)$$

where

V_{TR} = Relative tip speed of last rotor of the turbine. If V_{TR} is unknown, use 0.7 times the tip speed.

V_R = Reference velocity, 0.305 M/S (1 fps)

$\dot{m}$ = Primary mass flow

$\dot{m}_R$ = Reference mass flow, 0.4536 KG/S (1 lbm/sec)

C_L = Speed of sound at the turbine exit. If C_L is unknown, use

$C_L \simeq a\sqrt{T_{T7}}$ with a = 19.8 M/S per $(^\circ K)^{0.5}$ = 48.5 fps per $(^\circ R)^{0.5}$

T_{T7} = Turbine exit total temperature

C_R = Reference speed of sound, 340.3 M/S (1116 fps)

M_o = Aircraft Mach number

ξ = Angle between direction of aircraft motion and sound propagation path

θ = Directivity angle from the inlet axis

F_1 = Empirical curve shown in Figure 5a.

Sample data and predicted results are shown in Figure 2. The 1/3 octave band spectrum shape is shown in Figure 6. The sound pressure level spectrum is defined as

$$SPL(f) \simeq SPL_{peak} + F_2(f/f_o) \qquad (2)$$

where
F_2 = Function shown in Figure 6a.
f_o = fundamental blade passage frequency of the last rotor stage of the turbine

= $B\dot{\theta}/(60\ (1-M_o\ \cos\xi))$

B = Number blades for the last rotor stage of the turbine

$\dot{\Theta}$ = Shaft speed in rpm

The spectrum is extrapolated to a radius of one meter using

$$SPL(f)\Big|_{1\ M} = SPL(f)\Big|_{45.7M} + 33.2 + \Delta dB(f)\Big|_{Atm.\ Absorption} \qquad (3)$$

Discrete tone component - The discrete tone component of turbine noise is defined in a manner similar to that for broadband noise. The level of the fundamental tone at 45.7M (150 ft) from the source is given by

$$SPL_{tone} \simeq 10\log_{10}\left[\left(\frac{V_{TR}}{V_R}\right)^{0.6}\left(\frac{C_R}{C_L}\right)^{3}\left(\frac{\dot{m}}{\dot{m}_R}\right)\left(\frac{C}{S}\right)(1 - M_0\cos\xi)^{-4}\right] \qquad (4)$$

$$+ F_3(\theta) + 56 + K$$

where F_3 = Emperical curve shown in Figure 5b.

C/S = stator/rotor spacing shown in Figure 7.

K = correction for turbofans with a primary nozzle exit plane upstream from the secondary nozzle exit plan, i.e., the JT8D

$\simeq$ -10 dB for the JT8D

$\simeq$ 0 dB for dual exhaust systems with co-planar exits, or turbojets

The frequency of the fundamental tone corresponds to the blade passage frequency, f_0 above. The higher harmonics are assumed to fall off at 10 dB per harmonic number as shown in Figure 6b.

The tones are added to the broadband spectrum (eq. (2) above) before the extrapolation to index (R=1M) conditions is made. After the extrapolation the resulting spectrum represents the turbine noise at the free-field, index condition.

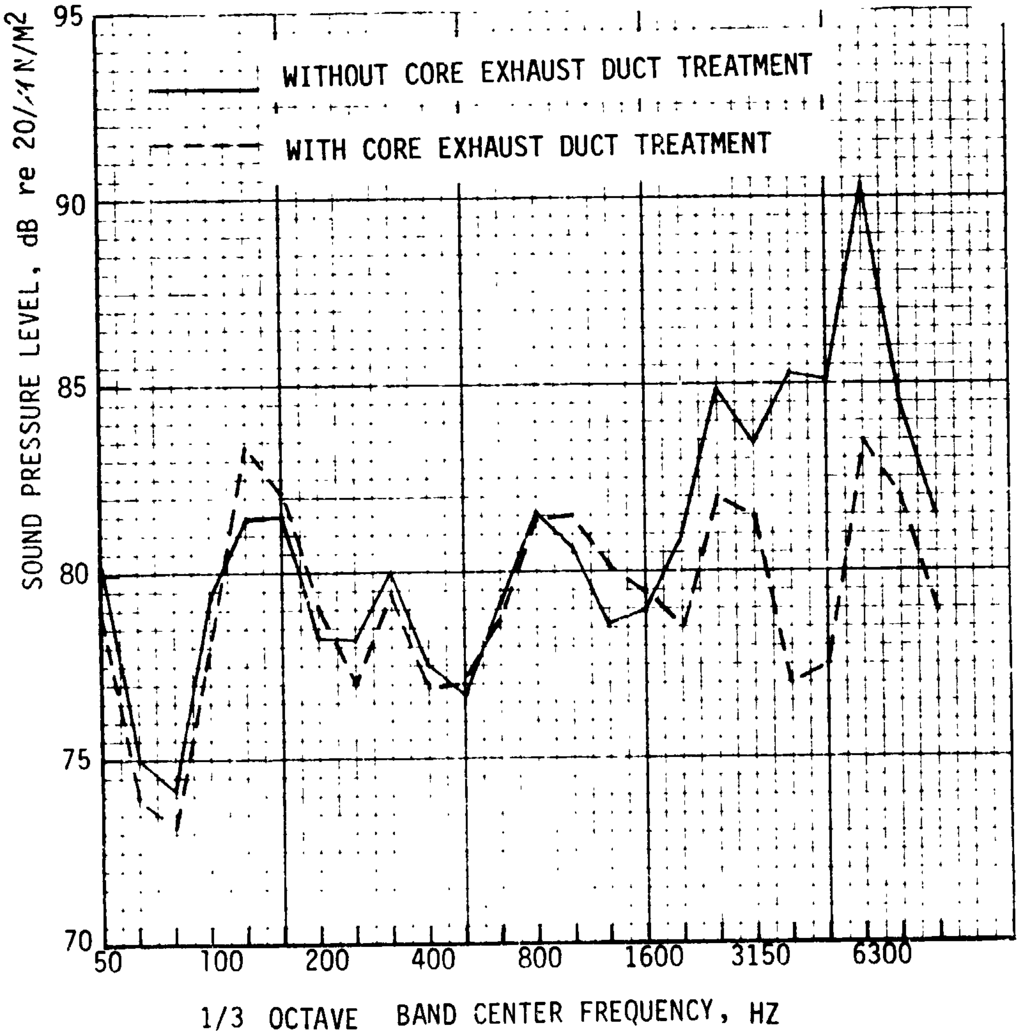

FIGURE 1 - EFFECT OF CORE EXHAUST DUCT ACOUSTIC TREATMENT ON 1/3 OCTAVE BAND SPECTRA OF QUIET ENGINE C. DISTANCE = 45.7M (150 FT) AT 120° FROM INLET AXIS. (DATA FROM REF 2)

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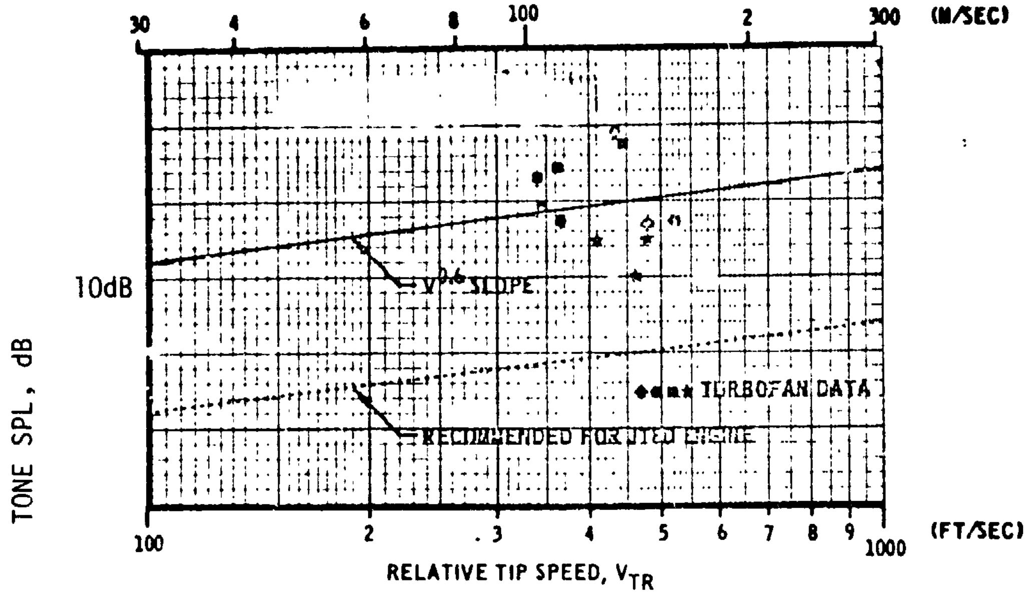
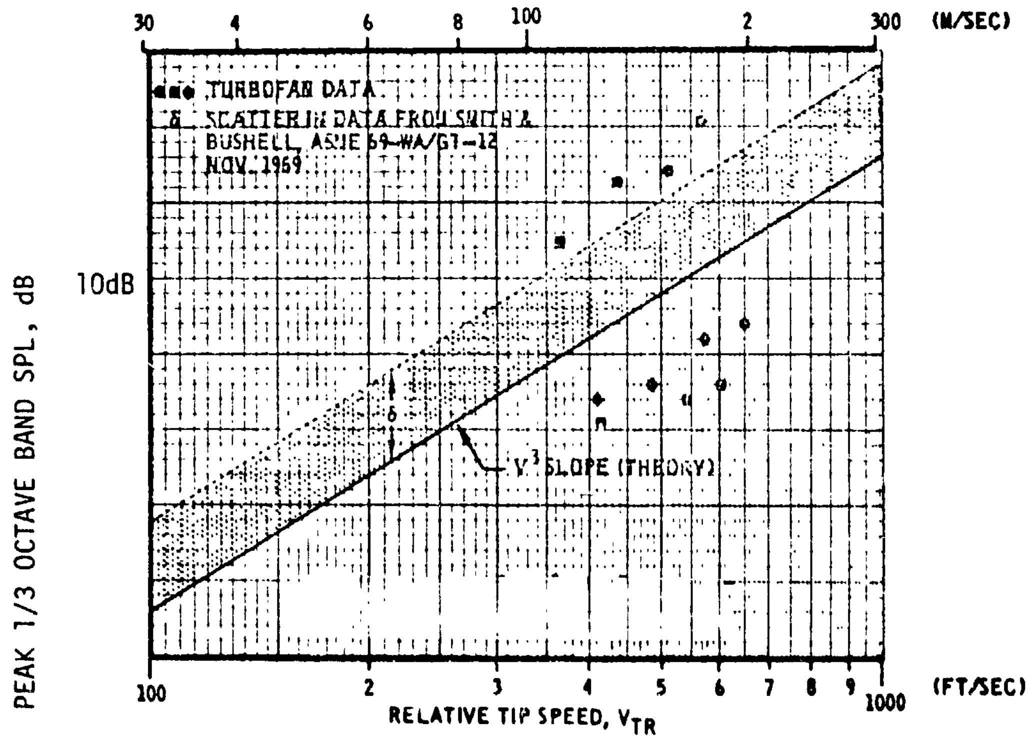


b) FUNDAMENTAL TONE



a) BROADBAND NOISE

FIGURE 2 - RELATIVE SOUND PRESSURE LEVELS AS MEASURED AND PREDICTED (FROM REF. 2)

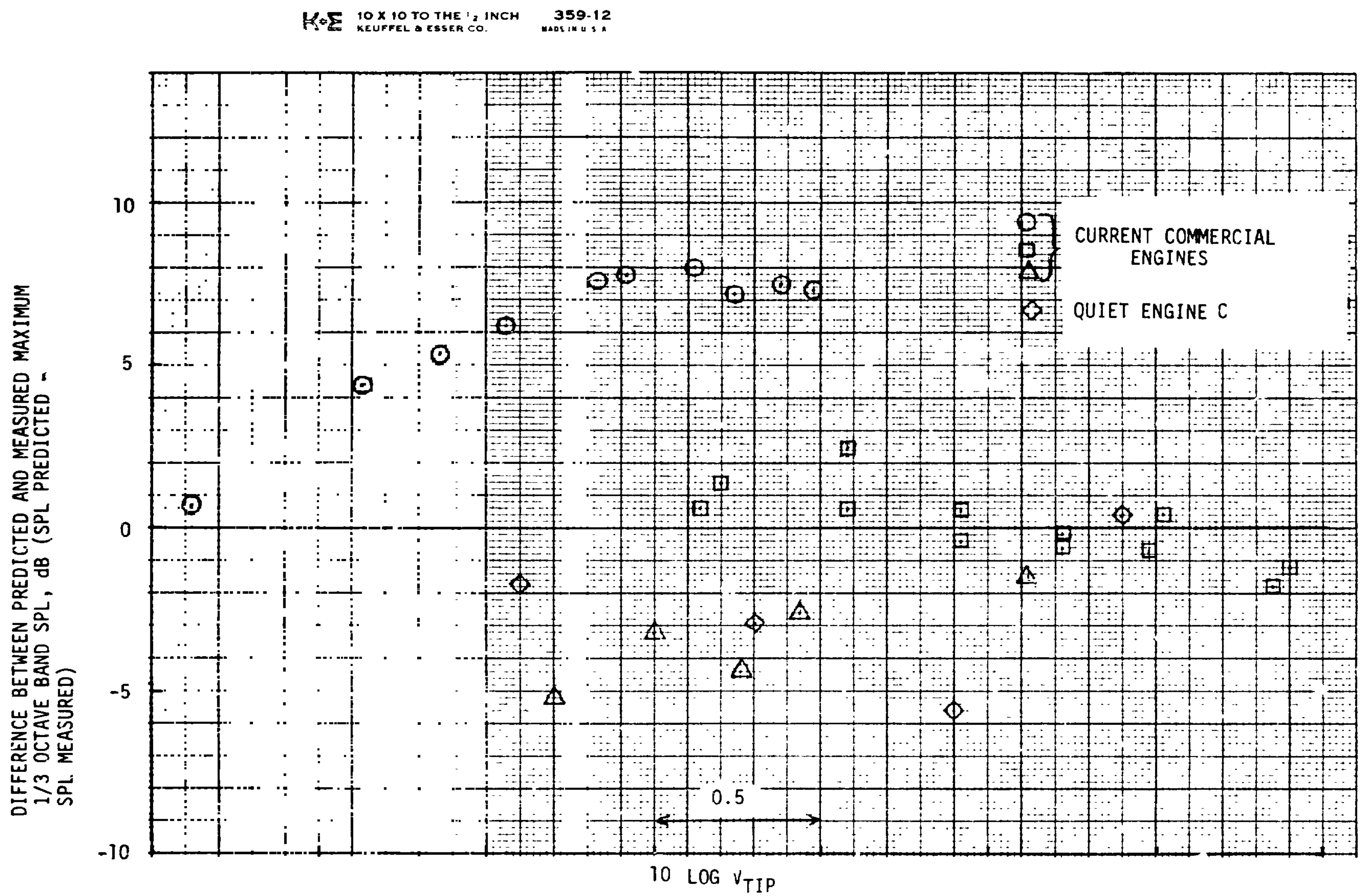


FIGURE 3 - DIFFERENCE BETWEEN PREDICTED TURBINE NOISE, USING METHOD OF REFERENCE 3, AND MEASURED TURBINE NOISE PLOTTED AGAINST LOG V_{TIP}

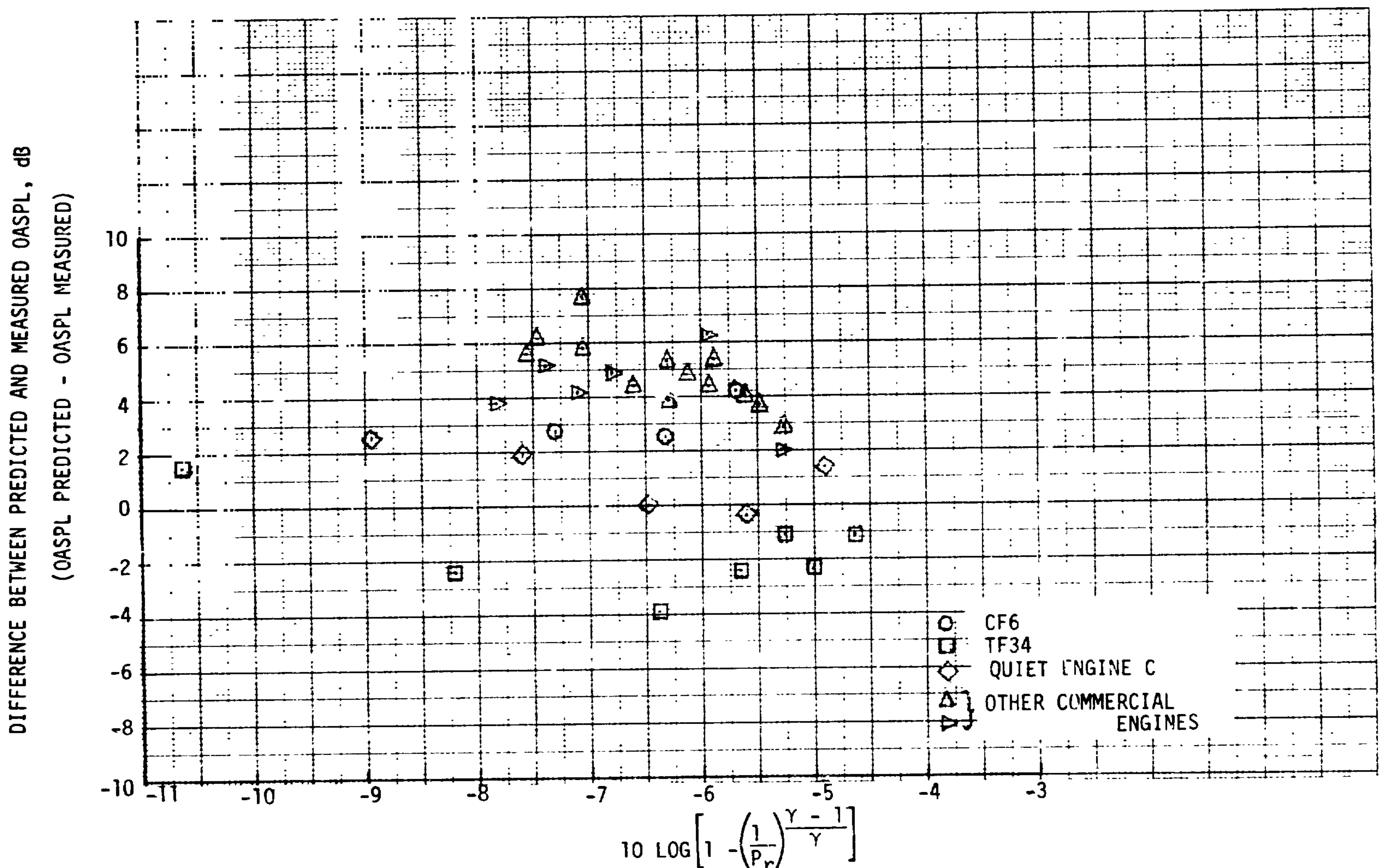
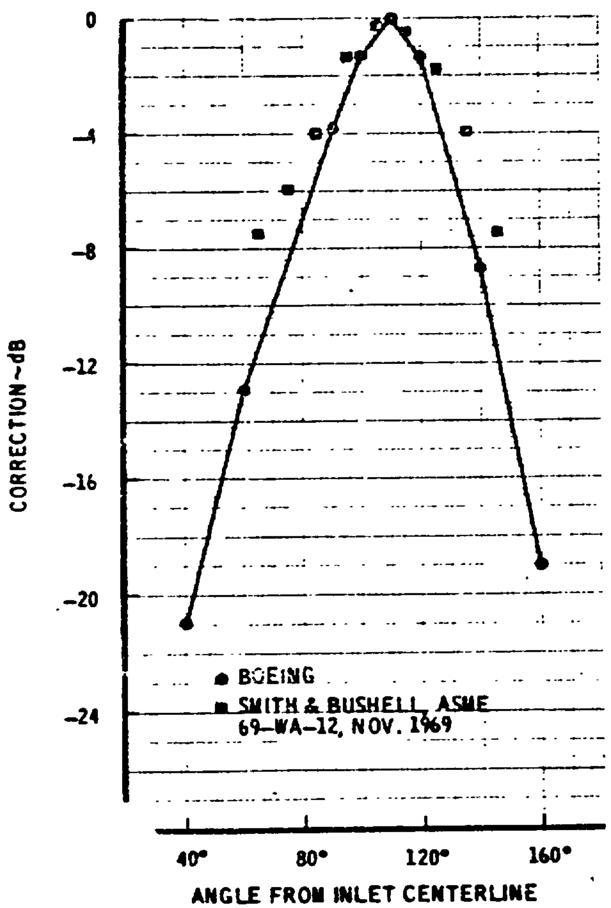
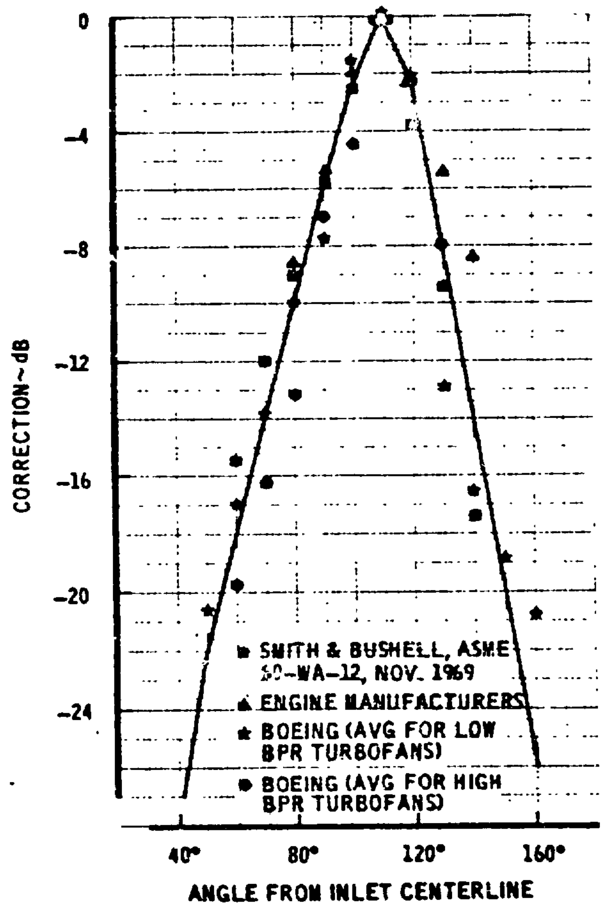


FIGURE 4 - DIFFERENCE BETWEEN PREDICTING TURBINE NOISE, USING THE METHOD OF REFERENCE 5, AND MEASURED TURBINE NOISE PLOTTED AGAINST TURBINE PRESSURE STATIC FUNCTION



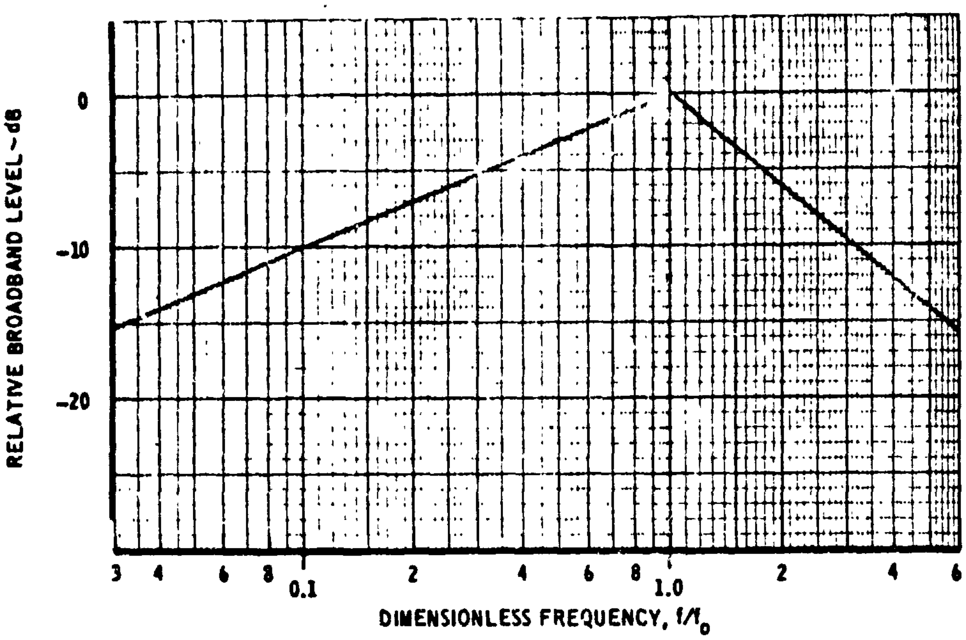
a) BROADBAND NOISE



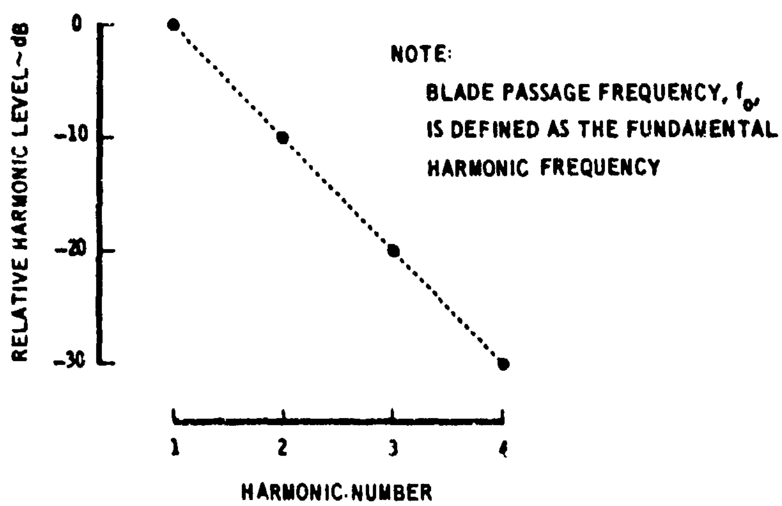
b) DISCRETE TONE

FIGURE 5 –TURBINE NOISE DIRECTIVITY CORRECTIONS

· DATA HAS BEEN AVERAGED AND ADJUSTED TO PEAK AT θ - 110

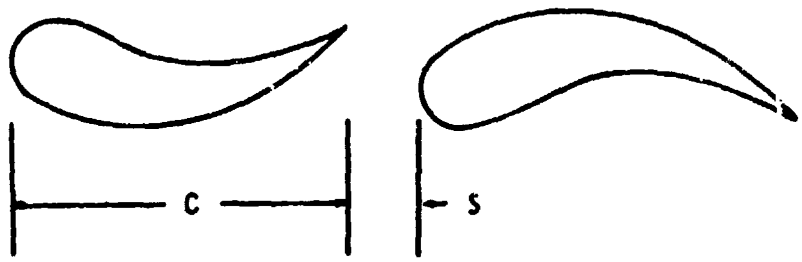


a) BROADBAND NOISE



b) DISCRETE TONES

FIGURE 6 –TURBINE NOISE SPECTRUM SHAPE



STATOR ROTOR SPACING EQUALS C / S

FIGURE 7 –DEFINITION OF STATOR-ROTOR SPACING FOR TURBINES